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THE NATION'S LABORATORY FOR ADVANCED AUTOMOTIVE TECHNOLOGY

No. 13699



## *INCREASED DIESEL ENGINE AIR UTILIZATION ANALYSIS: CLOSER TO STOICHIOMETRIC COMBUSTION*

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<b>16. Abstract ( Limit: 200 words )</b>  Large gains in propulsion system reduction can be achieved by moving closer to stoichiometric combustion in diesel engines. This paper is intended to identify possible fuel injection and combustion strategies to achieve higher diesel engine power density via improved air utilization.  The following technology should be addressed for near-term solutions to better air utilization in diesel engines. Utilize high pressure injection equipment that has flexible rate shaping and the smallest possible injector holes. Ideally, fuel injection systems that can control split injections are needed.  The appropriate combustion chamber is the quiescent chamber to match the high injection pressures and a shallow combustion bowl. It is necessary to eliminate dead-volumes by moving the top piston ring as close to the crown as possible and reducing the piston-to-cylinder head clearance. If possible, it is advisable to use flush mounted valves and eliminate valve pockets.  Increased turbocharger boost would allow smaller engine packaging. Methods to control peak cylinder pressure should be considered.  The most promising long-term technology is the Homogeneous Charge Compression Ignition (HCCI) combustion process. Stoichiometric combustion is possible without visible smoke. Further development of this system is necessary for this to be a viable solution.			
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## CONTENTS

	Page
REPORT DOCUMENTATION PAGE . . . . .	<i>i</i>
LIST OF FIGURES . . . . .	<i>v</i>
1.0 SUMMARY . . . . .	1
2.0 INTRODUCTION . . . . .	2
3.0 INJECTION TECHNOLOGY . . . . .	3
3.1 Summary of Injection Equipment . . . . .	3
3.1.1 Pump-Line-Nozzle (PLN) . . . . .	3
3.1.2 Unit Injector . . . . .	4
3.1.3 High Pressure Common Rail (HPCR) . . . . .	4
3.1.4 Hydraulically Actuated Electronically Controlled Unit Injector (HEUI) . . . . .	5
3.1.5 Unit Pump . . . . .	6
3.2 High Injection Pressure . . . . .	6
3.2.1 Benefits . . . . .	6
3.2.2 Limitations . . . . .	7
3.3 Smaller Injection Hole Diameters . . . . .	7
3.3.1 Benefits . . . . .	7
3.3.2 Limitations . . . . .	8
3.4 Rate Shaping . . . . .	9
3.4.1 Conventional: Good Cam . . . . .	9
3.4.2 Pilot Injection . . . . .	9
3.4.3 Advanced Rate Shaping . . . . .	10
3.4.4 Split Injection . . . . .	10
3.5 Multiple Injection Sites . . . . .	11
4.0 COMBUSTION TECHNOLOGY . . . . .	13
4.1 Conventional Combustion Chamber Design . . . . .	13
4.1.1 k-factor . . . . .	13
4.1.2 Optimize Combustion Bowl . . . . .	14
4.2 Increased Turbocharger Boost . . . . .	15
4.2.1 Benefits . . . . .	15
4.2.2 Limitations . . . . .	15
4.3 Indirect Injection . . . . .	15

## CONTENTS (Cont'd)

	Page
4.3.1 Benefits . . . . .	15
4.3.2 Limitations . . . . .	16
4.4 Direct Injection and Indirect Injection (DI+IDI) . . . . .	16
4.4.1 Benefits . . . . .	16
4.4.2 Limitations . . . . .	16
4.5 Homogeneous Charge Compression Ignition (HCCI) . . . . .	16
5.0 OXYGEN ENRICHMENT . . . . .	18
6.0 CONCLUSIONS/RECOMMENDATIONS . . . . .	19
6.1 Near-Term Technologies . . . . .	19
6.1.1 Injection Equipment . . . . .	19
6.1.2 Combustion Bowl . . . . .	19
6.1.3 Increased Turbocharger Boost . . . . .	19
6.1.4 Oxygen Enrichment . . . . .	19
6.2 Long-Term Technologies . . . . .	19
7.0 REFERENCES . . . . .	20

## LIST OF FIGURES

Figure		Page
1	Bosch Smoke versus Air-Fuel Ratio . . . . .	2
2	Pump-Line-Nozzle Injection System . . . . .	3
3	Cross-Section of an In-Line Pump . . . . .	3
4	Schematic of a Unit Injector . . . . .	4
5	Available Injection Pressure of a HPCR System as Compared to Conventional Injection Systems . . . . .	4
6	Cross-Section of a HEUI Injector . . . . .	5
7	Available Injection Pressure of a HEUI System as Compared to Conventional Injection Systems . . . . .	5
8	Plume Penetration Rate versus Time for Various Injection Pressures . . . . .	7
9	Indication of Air Utilization for Various Injection Pressures . . . . .	7
10	Plume Penetration versus Time for Two Different Nozzle Hole Sizes and Constant Injection Pressure and Flow Area . . . . .	8
11	Indication of Air Utilization for Two Different Nozzle Hole Sizes and Constant Injection Pressure and Flow Area . . . . .	8
12	Number of Nozzle Holes as a Function of Hole Diameter for Constant Mass Flow and Injection Pressure . . . . .	8
13	Illustration of Concept to Intersperse Larger and Smaller Nozzle Hole Sizes and Plume Spray Angles to Enhance Air Utilization . . . . .	9
14	Conventional Injection Profile as Compared to a Pilot and Main Injection Profile . . . . .	9
15	Calculated Pressure Distribution in a Standard and VCO Nozzle . . . . .	10
16	Ideal Injection Rate Shape as a Function of Engine Speed and Load . . . . .	11
17	Cylinder Pressure, Apparent Heat Release Rate, and Injection Rate for Triple Injections at 75% Load . . . . .	11
18	Shallow Bowl Combustion Chamber . . . . .	13
19	Illustration of Swirl . . . . .	13
20	Deep Bowl Combustion Chamber . . . . .	14
21	Illustration of Squish . . . . .	14
22	Illustration of k-factor . . . . .	14
23	Cross-Section of a Steel Piston Crown . . . . .	15
24	Cross-Section of an IDI Combustion Chamber . . . . .	16

## **1.0 SUMMARY**

The following is a summary of the possible fuel injection and combustion strategies to achieve higher diesel engine power density via improved air utilization.

### **Near-Term Technologies**

The following technology should be addressed for near-term solutions to better air utilization in diesel engines.

#### ***Injection Equipment***

- Utilize high pressure injection equipment that has flexible rate shaping.
- The most commercially viable injection systems are the High Pressure Common Rail (HPCR) and the Hydraulically actuated Electronically controlled Unit Injector (HEUI).
- Ideally, fuel injection systems that can initiate and control split injections (as many as three per cycle) are needed. Initial development should begin with pilot and main injections and then proceed with multiple injections for smoke and peak cylinder pressure control.
- The smallest injector holes should be used. However, it should be noted that the number of holes should not be too numerous that the fuel jets overlap.

#### ***Combustion Bowl***

- The appropriate combustion chamber is the quiescent chamber to match the high injection pressures.
- Utilize a shallow combustion bowl.

- It is necessary to move the top piston ring as close as possible to the top of the piston crown to lessen the crevice volume, reduce the piston-to-head clearance, utilize flush mounted valves, and eliminate valve pockets if possible.

### ***Increased Turbocharger Boost***

- Increase air density by increasing the turbocharger boost directly decreases engine size by allowing smaller cylinders while producing the same power. Methods of controlling peak cylinder pressures must be employed. Ideally, increased cylinder pressure design limits are encouraged.

### ***Oxygen Enrichment***

- DuPont Automotive has developed a membrane that increases oxygen content in the air (volume percent). A trade-off between space consumed and the pressure drop of the Compact Membrane System™ versus the power increase or engine reduction should be conducted.

### ***Long-Term Technologies***

- The most promising long-term technology is the Homogeneous Charge Compression Ignition (HCCI) combustion process. Stoichiometric combustion is possible without visible smoke. Further development of this system is necessary before viability can be assessed.
- Other technologies such as multiple injectors or DI+IDI combustion chambers may be undesirable due to the increasing hardware and control complexities.

## 2.0 INTRODUCTION

A Blue Ribbon Propulsion Committee was commissioned to identify methods to reduce the size of the propulsion systems for Army combat vehicles. One of the committee conclusions was that large gains in propulsion system reduction can be achieved by moving closer to stoichiometric combustion in a diesel engine. This paper is intended to identify possible fuel injection and combustion strategies to achieve higher diesel engine power density via improved air utilization. According to Raffelsberger et al. [1995], combustion properties of a high speed DI diesel engine are influenced in the following manner: 60-70 percent by the injection system, 15-20 percent by the engine structural design, and 15-20 percent by the combustion chamber properties.

Diesel engines operate in an overall lean mode. When air-fuel ratios drop below 20:1, smoke and particulates increase dramatically. This is illustrated by Figure 1 of smoke versus air-fuel ratio. These data were collected at SwRI from many different diesel engines.

Burning closer to stoichiometric combustion requires better air utilization. Air utilization is defined as the percentage of air actually participating in combustion when compared to the overall engine air flow. What does this mean for combat vehicles? Either the engine displacement (size) can remain the same and the power output increased, or the power output held constant while reducing the engine displacement.

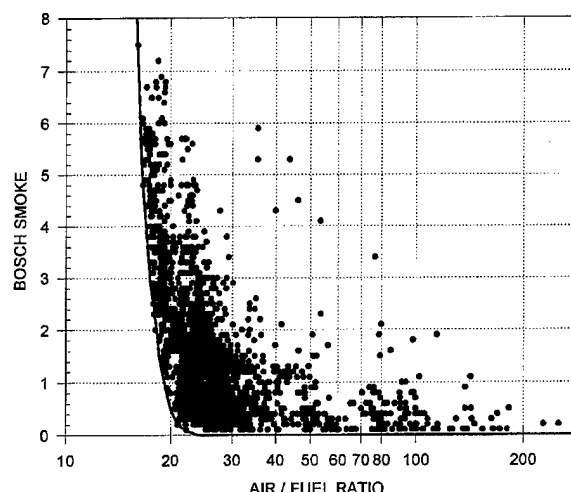


Figure 1. Bosch Smoke versus Air-Fuel Ratio



## 3.0 INJECTION TECHNOLOGY

There are many emerging injection technologies that will allow better air utilization in diesel engines. This discussion begins with a brief summary of injection equipment. The discussion follows with injection technologies such as: high injection pressure, small injector holes, injection rate shaping, and multiple injections.

### 3.1 Summary of Injection Equipment

There are five types of fuel injection equipment (FIE): pump-line-nozzle, unit injectors, high pressure common rail, hydraulic electronic unit injector, and unit pump. Each system is described below.

#### 3.1.1 Pump-Line-Nozzle (PLN)

The pump-line-nozzle system is named so after its hardware configuration. A high pressure pump delivers the fuel to the nozzle through a high-pressure injection line. There are two general types of PLN systems: in-line and distributor pumps.

The in-line pump utilizes one plunger for each of the engine cylinders. A schematic of this system is shown in Figure 2. A fuel supply pump provides low pressure fuel to the main injection pump gallery. Plungers compress the fluid to achieve the high injection pressure. The high

pressure diesel fuel is transferred to the nozzle by an injection line. The plungers are driven by the injection pump's cam which is usually geared to the engine's cam shaft (4-cycle). A cut-away of an in-line injection pump showing the plunger is given in Figure 3. The maximum injection pressure for an in-line PLN system is approximately 1200 atm (17.6 kpsi).

A distributor pump has only one pumping element and it must supply fuel to all the engine cylinders. The plunger stroke is coordinated with a rotating cam plate. The maximum injection pressure for a distributor PLN system is approximately 750 atm (11 kpsi).

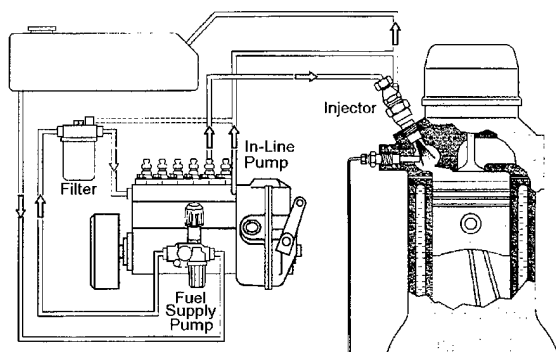


Figure 2. Pump-Line-Nozzle Injection System  
[Reference: Bosch Technical Instruction: Governors for Diesel In-Line Fuel-Injection Pumps]

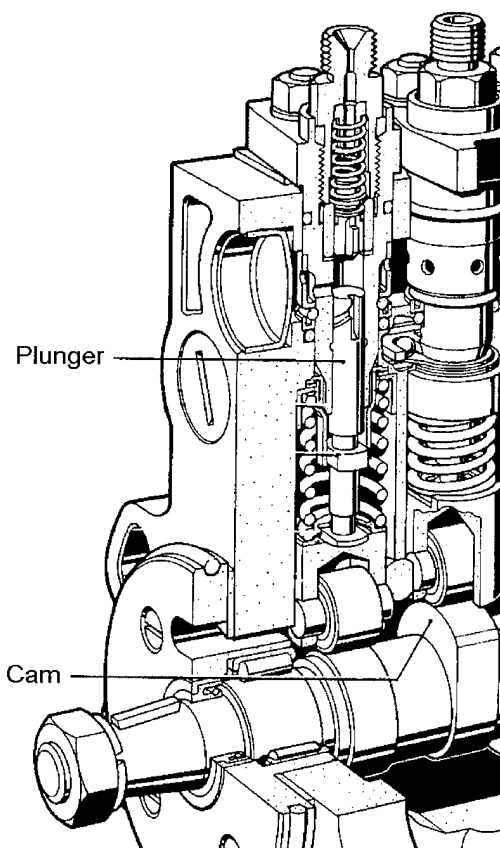


Figure 3. Cross-Section of an In-Line Pump  
[Reference: Bosch Technical Instruction: Diesel Fuel Injection—An Overview]

The maximum injection pressures generated by PLN systems are not only limited by the structural strength of the pump itself, but by the large volume in the high pressure lines (sometimes called "dead-volume"). Energy is lost during the compression due to viscous work on the fuel and injection line expansion. In addition, pressure waves traverse the injection line and are reflected at each end. This makes control difficult and may generate undesirable secondary and tertiary injections or cavitation.

### 3.1.2 Unit Injector

A unit injector is an integrated pump and injector for each cylinder directly installed in the cylinder head and is actuated by the engine cam. There are two types of unit injectors: mechanical unit injector (MUI) and electronic unit injector (EUI). Injection timing with MUI systems may be controlled hydraulically. With EUI systems, the injection timing and fuel quantity is controlled electronically via a rapid-action solenoid valve which controls the start of injection and injected fuel quantity. Injection pressures up to 2000 atm (29 kpsi) are possible. See Figure 4 for a schematic of a unit injector. The unit injector is commonly used in high-power heavy-duty diesel engines. The unit injector has a very short path for high pressure fuel which solves the problems of the PLN system's dead-volume.

### 3.1.3 High Pressure Common Rail (HPCR)

The common rail system has been in existence for many years. One "modern" version of this system was developed by Nippondenso (ECD-U2). It uses a high pressure feed pump to pressurize a common rail to a desired pressure which varies with engine speed and load. Injection quantity and timing is electronically controlled by pulse-width modulation. The injection rate can be controlled in three different shapes: delta, boot and pilot. The peak

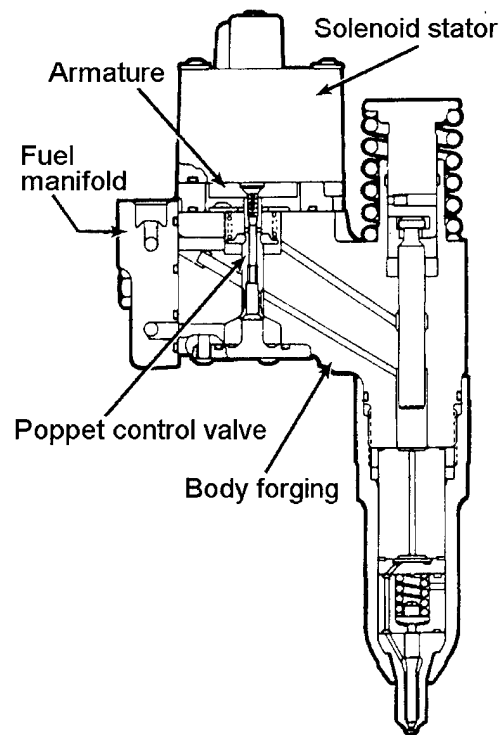


Figure 4. Schematic of a Unit Injector  
[Reference: Heywood]

injection pressure dependence on engine speed is much more favorable than conventional injection systems. The peak injection pressure is nearly realized within the first quarter of pump speed (see Figure 5). Peak injection pressures for this HPCR currently is 1200 atm (17.6 kpsi). Much higher peak injection pressures can be achieved by incor-

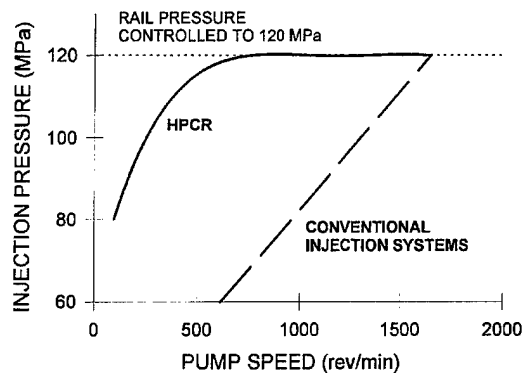


Figure 5. Available Injection Pressure of a HPCR System as Compared to Conventional Injection Systems [Reference: SAE 910252]

porating intensifiers within the injectors. With these intensifiers, the peak injection pressure is even greater than the common rail pressure. A disadvantage of the HPCR system is that at extremely high pressures, the power consumption of the fuel system may be greater than the power increased or as a result of better combustion.

### 3.1.4 Hydraulically Actuated Electronically Controlled Unit Injector (HEUI)

The Hydraulically Actuated Electronically Controlled Unit Injector (HEUI), was developed by Caterpillar, Inc. It requires no mechanical actuating or mechanical control devices, and offers many advantages over conventional fuel injection systems. A high pressure oil pump supplies pressure to a hydraulic intensifier which compresses the diesel fuel. Features of the HEUI system include the following: injection pressure control independent of engine load or speed, totally flexible injection timing, and full electronic control of injection parameters. The hydraulic unit injection consists of three main components: control valve, intensifier plunger and barrel, and nozzle (see Figure 6 For a cross-section). The HEUI system provides very accurate metering of the fuel at all delivery rates and can be applied to provide pilot injection. The largest benefit to smoke control is the decoupling of peak injection pressure to engine speed. As shown in Figure 7, the conventional fuel system peak injection pressure has a dependence on engine speed. The HEUI system can provide high injection pressure over the entire engine operating range. This fuel injection system is currently utilized on the Navistar T 444E and Powerstroke engines. The peak injection pressure is dependent on the intensifier design. Current systems deliver a peak injection pressure of approximately 1400 atm (20.6 kpsi). Injection pressures of 2000 atm (29 kpsi) have been demonstrated with HEUI injection systems.

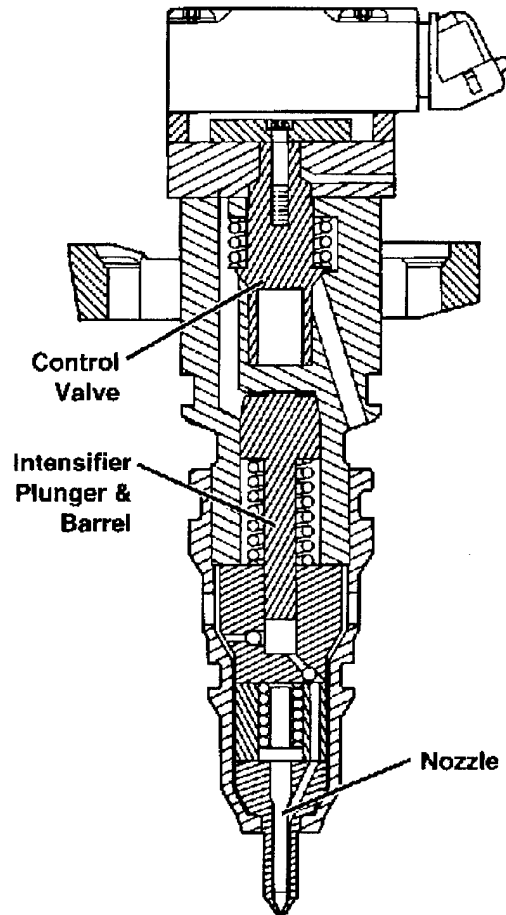


Figure 6. Cross-Section of a HEUI Injector  
[Reference: SAE 930270]

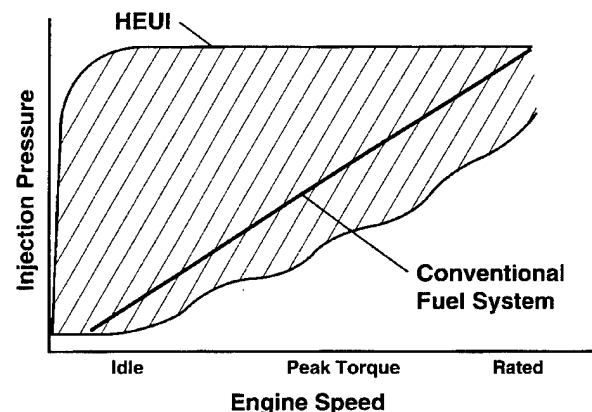


Figure 7. Available Injection Pressure of a HEUI  
System as Compared to Conventional  
Injection Systems

### **3.1.5 Unit Pump**

A unit pump is a cross between a unit injector and a PLN system. Each cylinder has an engine cam driven pump which is connected to an injector by a high pressure line. Injection quantity and timing may be electronically controlled. This system is utilized on locomotive engines where the physical distances are large and the fuel flow rate is high enough to eliminate using the fuel injection systems listed above. Maximum injection pressure is approximately 1200 atm (17.6 kpsi).

### **3.2 High Injection Pressure**

Diesel engine power is proportional to the amount of fuel burned. Reducing the mass of air required to burn a fixed amount of fuel will allow a reduction in engine size. Increasing the air density in the combustion chamber via higher turbocharger boost will also allow a reduction in engine size. This discussion addresses the first approach, improved air-fuel mixing.

The minimum amount of air required is fixed by the smoke limit for the engine. The smoke limit may be reduced to a lower air-fuel ratio if mixing is increased. Increased mixing is accomplished by mixing the fuel to lean of stoichiometric (about 14.6:1 air:fuel) within about 0.5 ms, before soot formation can occur in the rich combustion zones. This can be accomplished by: (a) increasing the injection pressure, (b) reducing the injector hole sizes, and (c) increasing the air density in the chamber. However, these changes must be made in concert with the combustion bowl to make sure that all the air in the chamber is utilized. This includes entraining air into the free fuel jet, before the jet hits the wall, and the wall jet. (Wall jet is the terminology for the fuel jet after it has impacted the wall and turned.)

Engine testing has demonstrated that about 5 to 9 holes in a diesel injector tip provide optimum utilization of air in the free and wall

jets for high-speed diesel engines. For much larger, medium and low-speed diesel engines where the wall jets are not so important, a larger number of holes may be used. Injection pressures and hole sizes are matched so that at rated speed and load, the injection event takes about 40 crank angle degrees. Longer injection events would produce heat release too late in the cycle for good thermal efficiency. Shorter injection events do not allow as much time for air-fuel mixing.

#### **3.2.1 Benefits**

In simplistic terms, by increasing injection pressure, more energy (or momentum) is provided to the fuel jet. In order to increase the air utilization of the engine, the fuel-air mixing rates in the free and wall jets must be increased. Fuel that is mixed to a lean equivalence ratio quickly is less likely to form particulates (and smoke) than fuel that is mixed more slowly. When fuel is burned at locally rich equivalence ratios, air utilization is much lower and higher smoke/particulates is a likely result. This only addresses particulates and the smoke signature, not the particulate NO<sub>x</sub> tradeoff. NO<sub>x</sub> is not considered critical in a combat vehicle.

The SwRI-developed jet mixing model, called JETMIX™, was engaged to obtain data for illustration. This model treats the fuel as a dense gas jet, and it uses conservation of the fuel mass flux and the jet momentum rate to evaluate mixing.

The trend over the years to improve air utilization and reduce smoke is to increase injection pressure and reduce hole sizes while maintaining injection durations about constant. The impact on penetration rates is shown in Figure 8. The increased injection pressures increase penetration rates significantly, while reduced hole sizes decrease penetration rates slightly, with the net results that, at a constant flow rate, the penetration rate increases. How-

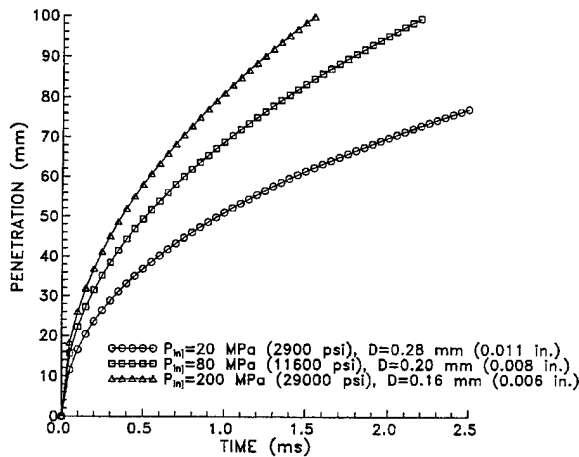


Figure 8. Plume Penetration Rate versus Time for Various Injection Pressures

ever, an increased penetration rate alone does not imply increased air-fuel mixing rates. Rather, the distribution of air-fuel ratios in the jet must be determined.

The air-fuel distribution in the jets shown in Figure 9 are for the same conditions as in Figure 8. Figure 9 shows the air-fuel distributions in the three jets frozen at 1.5 ms from the start of injection. Fuel mixed to a fuel-air equivalence ratio of less than 1.5 will not form soot. (A fuel-air equivalence ratio of 1.0, corresponds to an air-fuel ratio by mass of about 14.6, or stoichiometric.) Note that for the high injection pressure of 200 MPa (29 kpsi) and

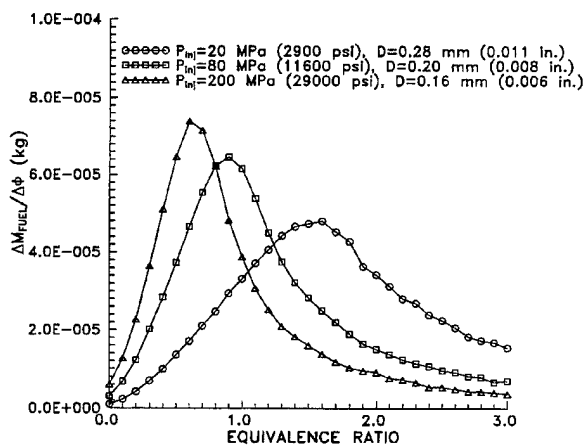


Figure 9. Indication of Air Utilization for Various Injection Pressures

hole size of 0.16 mm (0.0062 inch), most of the fuel is mixed to an equivalence ratio of less than 1.5 ms. The portion of the fuel which is richer than 1.5 equivalence ratio is in the jet very close to the tip and has not had enough time to form soot.

### 3.2.2 Limitations

The limitations of increasing injection pressure reside in the capability of the injection equipment. Injection pumps are limited by the structural strength of the design and the clearances in the pump. With stronger materials and closer tolerance machining, higher injection pressures can be achieved.

Another limitation of increasing injection pressure is the power required to pressurize the fuel. There is a point where the pump power consumption increases at a rate much faster than the benefits achieved in fuel-air mixing. In addition, combustion chamber optimization must follow increased injection pressures to achieve the full benefits. These limitations are likely to be dependent upon individual combustion systems.

### 3.3 Smaller Injection Hole Diameters

Engine manufactures are utilizing smaller injector hole diameters to increase fuel-air mixing, which, in turn, reduces visible smoke and particulates. In typical practice, the smallest hole diameter is selected to achieve maximum injection pressures at rated speed and power, while not exceeding 40 crank angle degrees injection duration.

#### 3.3.1 Benefits

The benefits of smaller injection hole diameters usually are realized in conjunction with higher injection pressures. The concept is that a larger number of injection holes will promote better fuel-air mixing.

The JETMIX™ model was utilized to evaluate two cases. The injection pressure and total flow

area remained constant. The first case contained an injector with 5 holes and a diameter of 0.20 mm (0.008 in). The second case contained an injector with 9 holes and a diameter of 0.15 mm (0.006 in). Reducing the hole size at constant injection pressure reduces the penetration rate as shown in Figure 10 for a reduction in hole size from 0.20 mm to 0.15 mm. However, reducing the hole size increases the air-fuel mixing rate as shown in Figure 11 where the smaller hole shows more fuel at the leaner fuel-air equivalence ratios (values of equivalence ratios less than 1.0 are lean).

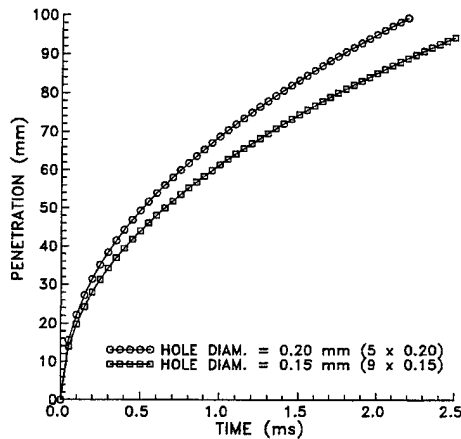


Figure 10. Plume Penetration versus Time for Two Different Nozzle Hole Sizes and Constant Injection Pressure and Flow Area

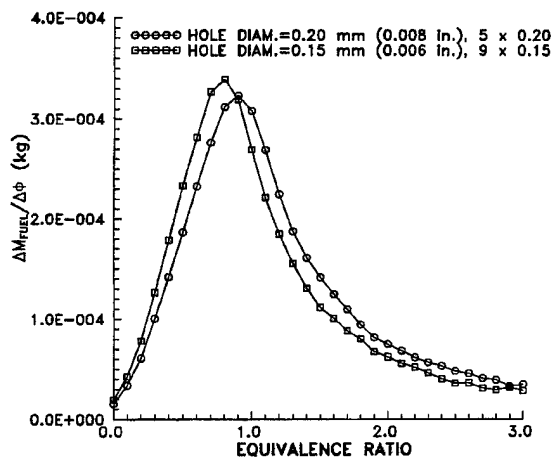


Figure 11. Indication of Air Utilization for Two Different Nozzle Hole Sizes and Constant Injection Pressure and Flow Area

### 3.3.2 Limitations

The limitations of smaller injection hole diameters is the actual manufacture of these holes and the survivability within the combustion chamber. As stated earlier, smaller injection hole diameters are usually used with higher injection pressures. Thus the injector tip must have a thicker wall to support the higher injection pressures. The L/D (length over hole diameter) increases dramatically. When the L/D exceeds 15, the roundness and quality of the hole is diminished, leading to poor injection spray qualities. Currently, the smallest hole in production is 0.15 mm. Smaller hole diameters also promote injector hole coking which degrades injection spray qualities. Coking is the build up of pyrolyzed fuel in the injection holes.

Significant reductions in hole size beyond today's state-of-the-art of about 0.15 mm (0.0059 inch) require a rapid increase in number of holes to keep injection rate constant for a constant injection pressure, as shown in Figure 12. To maintain a reasonable number of holes and to utilize all the air in the chamber, interspersing larger and smaller holes in a single tip might be possible, as shown in Figure 13.

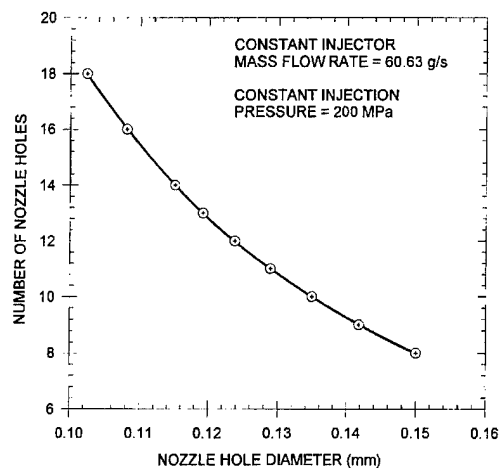


Figure 12. Number of Nozzle Holes as a Function of Hole Diameter for Constant Mass Flow and Injection Pressure

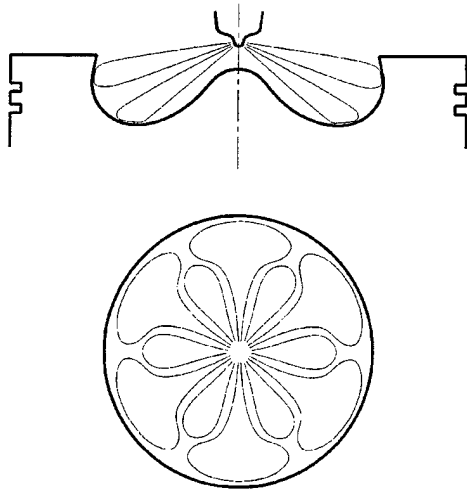


Figure 13. Illustration of Concept to Intersperse Larger and Smaller Nozzle Hole Sizes and Plume Spray Angles to Enhance Air Utilization

### 3.4 Rate Shaping

The term "rate shaping" is described as the active control over fuel injection rate during the injection event. Rate shaping includes complex ramp rates, pilot injection and even split injections. It is a broad term that describes a large quantity of research in the past few years. DI diesel engine developers realize that full control over the injection event is necessary to push the diesel engine to the next level.

Most of the research in rate shaping has been pursued with the intent of reducing emissions. This can loosely be applied to the need for better air utilization. By introducing the fuel into the combustion chamber in multiple stages, air utilization may be enhanced.

High power output requires heat release control to prevent high in-cylinder temperatures and to prevent exceeding peak cylinder pressure limits. Rate shaping has been used to provide heat release rate control. The following sections briefly describe various rate shaping topics. A complete list of papers found during the literature search was provided in the Informal Technical Report written on this work directive.

#### 3.4.1 Conventional: Good Cam

Circa 1990, rate shaping was done with the appropriately shaped cam and unit injectors. By changing the cam profile, the start of injection slope can be altered. The benefit of this system is that it is simple. The limitation is, however, that one rate shape was chosen for all engine speeds and loads. Ideally, the rate shape would be optimized over the entire speed and load range. This approach does provide an increase in air utilization. A fully flexible system would, however, provide better air utilization.

#### 3.4.2 Pilot Injection

Pilot injection is the scheme where a small amount of fuel is introduced into the combustion chamber prior to the main injection. The pilot fuel initiates the combustion process without the dramatic peak in the heat release rate. The addition of the pilot injection decreases the ignition delay of the main injection and slows the heat release rate. A conventional injection event is compared to a pilot and main injection event in Figure 14.

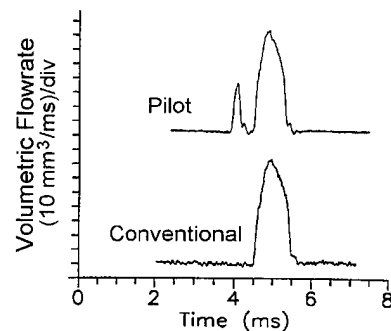


Figure 14. Conventional Injection Profile as Compared to a Pilot and Main Injection Profile

Beck and Chen [1990] have found that the fuel quantity of the pilot should be less than 10 percent of the total fuel injected. The duration of the pilot should be approximately equal to the ignition delay period. The size and position of the pilot affects the heat release rates and pressure history of the combustion

chamber. Beck and Chen also suggest that the pilot should be as close to the main injection—even attached too the main event, if possible. Both soot and NO<sub>x</sub> levels can be lowered when a properly sized and positioned pilot injection is used. Shundoh et al. [1992] show that the combination of pilot injection and injection pressure controls simultaneously reduce NO<sub>x</sub> by approximately 35 percent and smoke by 60 to 80 percent without worsening the fuel consumption.

The general method of achieving pilot injection is with the use of two injection pumps connected to the same injection lines. One pump provides the pilot injection while the other, provides the main injection. Some of the latest unit injectors have the capability of providing pilot injection. The newer injection equipment—HPCR and HEUI—can also provide pilot injections.

Providing a pilot injection attached to a main injection can be achieved by lifting the injection needle and holding it partially open for the length of the pilot injection. Okajima [1991] and associates maintain that injection rate should not be controlled by the seat throttling, but by the throttling of hole area. In a standard injector, seat throttling does not change the hole area during any portion of the needle lift which decreases real injection pressure and worsens the spray characteristics. In the valve covered orifice (VCO) and Improved nozzles, however, the hole flow area changes according to the hydraulic characteristics. The hydraulic characteristics change the effective flow area in proportion to needle lift. By this method, the fuel flows under higher pressure and velocity in the hole of the VCO and Improved nozzle during small needle lifts. Okajima and associates used computer simulations to demonstrate this concept. The results of the computer simulation is shown in Figure 15.

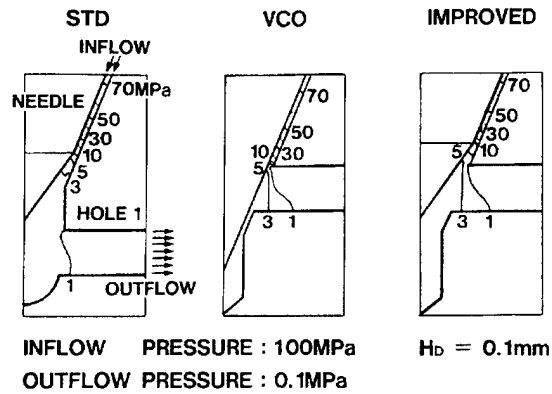


Figure 15. Calculated Pressure Distribution in a Standard and VCO Nozzle

### 3.4.3 Advanced Rate Shaping

Beck and Chen [1990] state an ideal injection event consisting of the following. The pilot should be connected to the main event, have a total fuel quantity of less than 10 percent of the main event, and a duration equal to the ignition delay period. The main injection should be at the highest practical pressure in the shortest practical time consistent with engine cylinder pressure limits. The end of injection should be accomplished in the shortest time possible, from a closing pressure in excess of 300 bar and without dribble or secondary injections.

Herzog [1989] has performed work to identify the ideal injection rate shape as a function of engine speed and load (see Figure 16). These injection rate shapes are one contiguous event which can provide excellent cylinder pressure control and enhanced air utilization. Separate injection events is a method to provide even more enhanced air utilization.

### 3.4.4 Split Injection

As stated earlier, most of the visible smoke/particulates emitted from diesel engines were generated at the end of the combustion cycle. Split injections are a method to address this issue by providing additional fuel later in the cycle to enhance mixing. Tow, Pierpont,



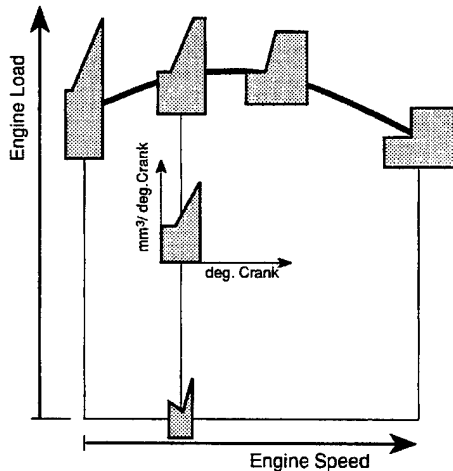


Figure 16. Ideal Injection Rate Shape as a Function of Engine Speed and Load

and Reitz claim that an important feature of split injection is that it can be used to increase fuel/air mixing and particulate oxidation rates late in the combustion period.

It is apparent from recent research that using a split injection has a significant impact on peak combustion pressure and rate of pressure rise (SAE 930864, 950217). One expected limitation to this technology is higher specific fuel consumption since the fuel is injected over a longer period of the cycle. Pierpont et al. [1995] have shown that multiple injections with relatively small quantities of fuel in the secondary pulses have little effect on specific fuel consumption. The distribution of the percent of fuel in each of the triple pulses was approximately 50, 35 and 15 percent. The increase in specific fuel consumption was less than two percent for a given NO<sub>x</sub> level.

Tow and colleagues [1994] have demonstrated that a relatively long dwell before the last injection appears to be effective for significant additional particulate reduction. In addition, the size of the dwell before the last injection is more critical than the quantity in the last injection. They have shown at 75% load, a triple injection scheme reduced particulates (and similarly, smoke) by a factor of

two with only a 1.5% increase in specific fuel consumption. A high speed combustion plot containing cylinder pressure, apparent heat release rate, and injection rate for the triple injections has been included in Figure 17.

The strategy of multiple injections appears to have the greatest impact on air utilization. The specifics on the quantities of fuel injected in each event as well as event spacing may be dependent on combustion chamber designs. A fully flexible fuel injection system is required to determine the optimum injection rate scheme.

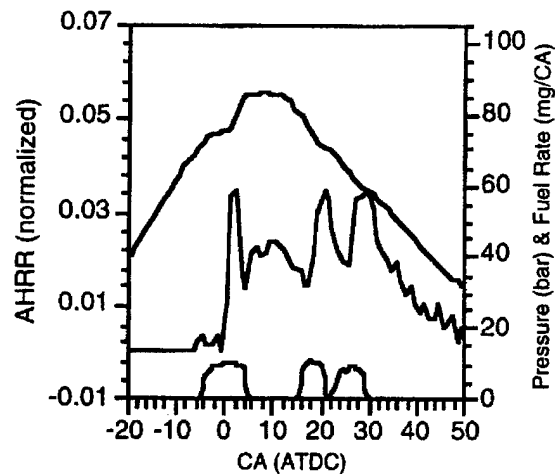


Figure 17. Cylinder Pressure, Apparent Heat Release Rate, and Injection Rate for Triple Injections at 75% Load

### 3.5 Multiple Injection Sites

Multiple injection sites is a proposed alternative to multiple injections through one injector. Two (or more) separate injectors can be placed in the cylinder head for each cylinder. Again, the idea is to utilize more air in combustion. Depending on the fuel handling system, the injection events could be staged, or one injector turned off during light loads. Most engines in today's production that utilize two injectors are ones that burn more than one type of fuel. Fairbanks Morse, a division of Coltec Industries, produces large stationary and marine engines (approximately 400 mm bore). In

an environmental retrofit package for opposed piston engines, Fairbanks Morse offers two direct injected diesel injectors as well as a pre-chamber and a pilot injector. This injection system has been demonstrated to substantially reduce emissions while increasing power (indication of better fuel-air mixing) and improving specific fuel consumption.

The limitations are the complexity of the fuel system and the additional costs involved. The future combat propulsion system is very likely to have a large number of medium-to-small bore sizes. Multiple injection points would probably not provide any additional benefits over a well matched nozzle/combustion chamber and multiple injections.

## 4.0 COMBUSTION TECHNOLOGY

Combustion technology is closely linked to the type of injection equipment; both are matched to achieve complete combustion. The following section discusses combustion chamber design, types of combustion chambers, and some novel approaches.

### 4.1 Conventional Combustion Chamber Design

The two ends of the spectrum for conventional Direct Injected (DI) diesel engines are deep bowl and shallow bowl combustion chambers. Shallow bowl combustion chambers, as shown in Figure 18, are utilized in large-bore, heavy-duty diesel engines. The chambers are sometimes called quiescent because the air motion is low. A measure of air motion which is generated by the intake ports is called swirl. An illustration of swirl is shown in Figure 19. The fuel-air mixing is solely dependent on high injection pressures and a large number of nozzle holes (range of eight to ten). Deep bowl combustion chambers, as shown in Figure 20, are utilized in medium-duty diesel engines. Moderate injection pressures require higher levels of swirl to provide complete fuel-air mixing. These combustion chambers also rely on squish to aid in mixing. Squish is the rapid air movement from the periphery of the piston crown into the combustion bowl as the piston rises to top dead center (see Figure 21). The typical number of injection holes for this system is four.

#### 4.1.1 k-factor

In order to discuss air utilization within combustion bowls, it is necessary to introduce a concept called "k-factor." The k-factor is the ratio of the bowl volume to the total compressed volume. This is illustrated in Figure 22. The air outside the combustion bowl does not participate very well in the combustion process.

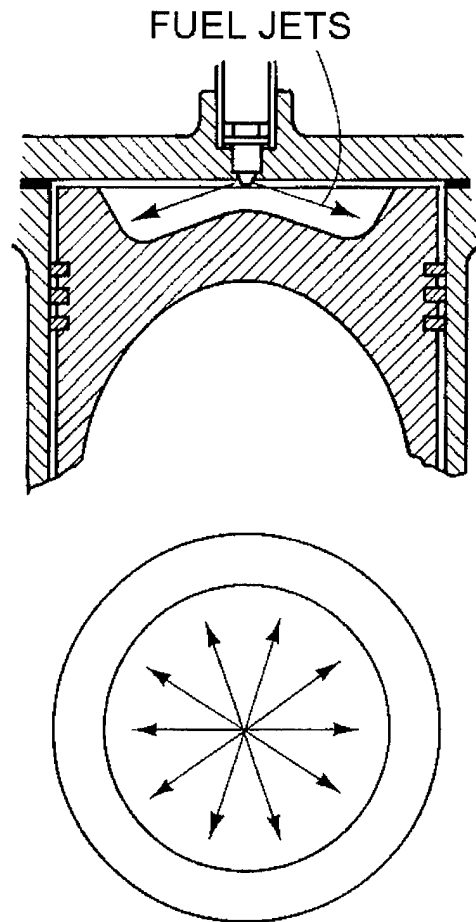


Figure 18. Shallow Bowl Combustion Chamber  
[Reference: Heywood]

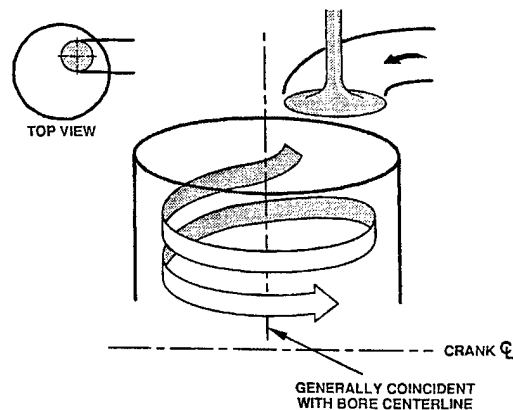


Figure 19. Illustration of Swirl

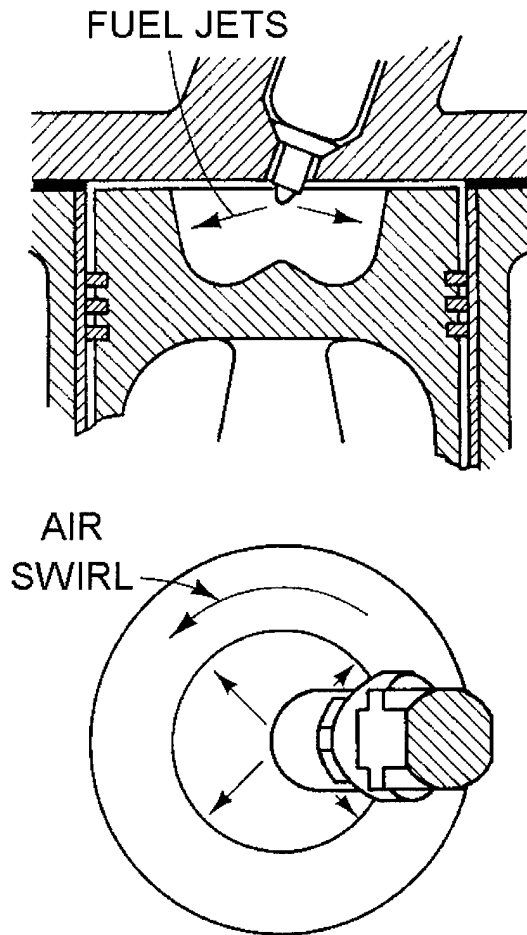


Figure 20. Deep Bowl Combustion Chamber  
[Reference: Heywood]

Some fuel may escape into this area, however, the fuel-air mixing rates are low.

A combustion chamber with a higher k-factor has higher air utilization. The shallow combustion bowl has a higher k-factor than the deep combustion bowl. Thus, it is desirable to have a shallow combustion bowl for higher air utilization.

#### 4.1.2 Optimize Combustion Bowl

In order to optimize the combustion bowl for best air utilization, the object is to remove the dead volumes. Minimizing the areas where combustion does not occur maximizes the air

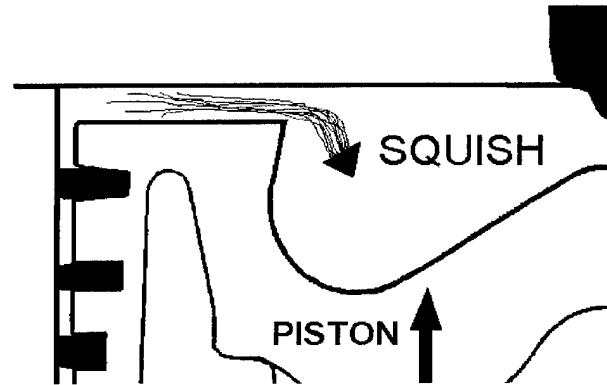


Figure 21. Illustration of Squish

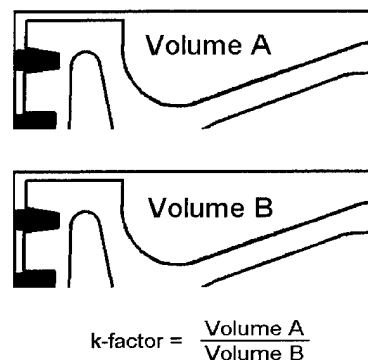


Figure 22. Illustration of k-factor

available for combustion. Ways of maximizing the air available to combustion are as follows:

- Utilizing a wider bowl to increase the k-factor. The limitation is that the bowl must be deep enough so that the fuel jets do not impinge on the bottom of the combustion chamber.
- Eliminating recesses. It is desirable to avoid recessing the valves. If volumetric efficiency does not suffer, it is also desirable to eliminate valve pockets in the piston crown.
- Moving the top piston ring as close to the top of the piston crown as possible to reduce the crevice volume. The limitation is that the material around the top ring must be strong enough to hold the ring in place during the combustion cycle. Some manufactures place ni-resist inserts in aluminum pistons to prevent groove

wear. Another option is to use a steel crown with an attached aluminum skirt. Heavy-duty diesel engine manufacturers use such a method for their heavy-duty engines. A cross-section of a Caterpillar steel combustion crown is shown in Figure 23.

- Reducing the piston-to-head clearance. The hot running clearance on current diesel engine is approximately 0.2 mm. As engine speed increases, the piston weight stretches the connecting rod. The hot running clearance is a function of engine speed and combustion temperatures. This clearance can be reduced further with lighter reciprocating masses (i.e., pistons and connecting rods), and stronger connecting rods.

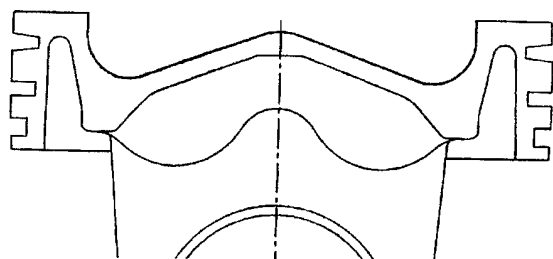


Figure 23. Cross-Section of a Steel Piston Crown

## 4.2 Increased Turbocharger Boost

Increased turbocharger boost is also an important way to reduce engine size and increase air-fuel mixing rates simultaneously.

### 4.2.1 Benefits

In terms of directly reducing engine size, using a higher turbocharger boost to increase the air density allows for smaller combustion chambers to be used to burn the same mass of air and fuel, still producing the same engine power. This results in a smaller engine package if the turbocharger size is maintained constant.

The increased boost increases the air-fuel mixing rate, reducing the mass of air required to burn a given amount of fuel without excess

smoke. A diesel jet entrains an almost constant volume of gas, independent of the gas density. Therefore, an increase in the jet density increases the mass of air entrained to mix with the fuel. This allows combustion of a given amount of fuel with less air.

### 4.2.2 Limitations

The fundamental limitation is maximum cylinder pressure limits. A certain design goal for a better air utilization engine would be to increase the maximum cylinder pressure limits.

Methods of controlling peak cylinder pressure can be utilized to solve this problem. Since NO<sub>x</sub> emissions are not a concern for a combat engine, advancing injection timing can be used for partial peak cylinder pressure control. More complex methods can be employed to aid in peak cylinder pressure control such as injection rate shaping and variable compression ratio engines. Moreover, the typical trade-off between intake boost pressure and compression ratio should be performed for an engine configuration.

## 4.3 Indirect Injection

Indirect Injection (IDI) is a combustion system where fuel is injected in a small chamber located in the cylinder head. The initial combustion begins inside the pre-chamber. When the pre-chamber pressure rises at the onset of combustion; fuel, air and flame are forced through the "throat." The flame issuing from the throat, sometimes called a torch, promotes vigorous mixing. The pre-chamber is shown, along with the injector and glow plug, in Figure 24.

### 4.3.1 Benefits

The benefits of IDI combustion is that the system generally has higher air utilization than the DI counterparts and use 10-15% less air. IDI combustion is less sensitive to injection timing than DI combustion. The injection pressures can be relatively low and less expensive injection equipment can be used. The combus-

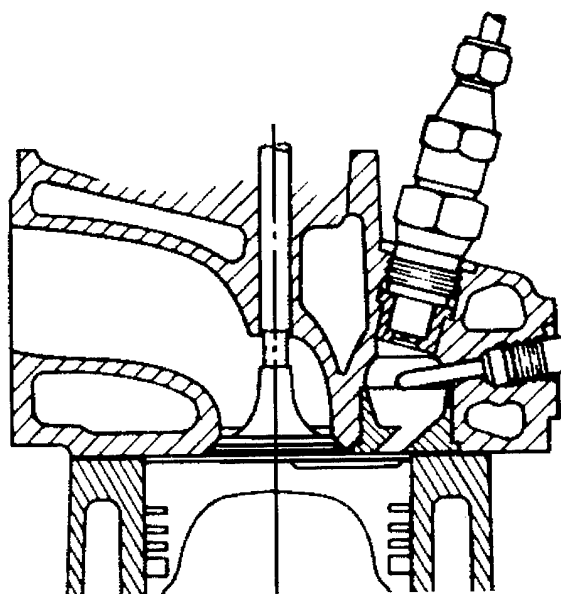


Figure 24. Cross-Section of an IDI Combustion Chamber [Reference: Heywood]

tion occurs over a longer period of time for IDI combustion than with DI combustion. Peak combustion temperatures are lower and the torch is an effective means to provide fuel/air mixing through the combustion process so that soot/particulates may be oxidized.

#### 4.3.2 Limitations

The main limitation to IDI combustion systems is that it has higher specific fuel consumption than the DI combustion systems. This is due to the large throttling and heat losses. The heat loss is a direct loss in power and added heat that the coolant must carry away. With the onset of new materials—namely ceramic composite; the throat area could be insulated to prevent high heat losses. Throttling losses, however, would remain.

#### 4.4 Direct Injection and Indirect Injection (DI+IDI)

During DI combustion, the visible smoke and soot that is emitted from the tail pipe is generated at the end of combustion. A concept of utilizing the IDI flame, or torch, to assist the end of combustion mixing has been discussed at SwRI. This is a very complex system

and is discussed as a possible enhanced mixing option.

##### 4.4.1 Benefits

The main combustion would occur as a typical DI system. However, a mini-post-chamber and micro-fuel-injector would be added to the cylinder head to provide end of combustion mixing. The added energy is thought to complete the soot oxidation process.

##### 4.4.2 Limitations

A high-power diesel engine would have four valves per cylinder. Cylinder head real-estate is in very short supply. It would be a very difficult design challenge to place a mini-post-chamber and micro-fuel-injector in the cylinder head. There would be a need for two fuel pressurization and delivery systems. The additional fuel added late in the cycle would be used for mixing enhancement and would not dramatically increase the power output. Thus, this combined system is expected to have a higher specific fuel consumption than a standard DI combustion system. Special attention must be taken with bowl design to account for the additional volume in the mini-post-chamber. It may be difficult to design working chambers and maintain the compression ratio.

#### 4.5 Homogeneous Charge Compression Ignition (HCCI)

In a compression ignition (CI) engine, injection timing controls the start of combustion. Combustion occurs in a diffusion flame controlled by mixing rate of the fuel (injected directly into the cylinder) and the charge air. High flame temperatures create high NO<sub>x</sub> emissions and the fuel rich zones behind the flame front cause high soot formation rates (and visible smoke).

HCCI is a process whereby a premixed charge of diesel fuel and air is admitted into the power cylinder and compression ignited. Ignition occurs homogeneously throughout the

cylinder. Homogeneous ignition eliminates high flame temperatures and reduces NO<sub>x</sub> emissions by approximately 98 percent. The lack of fuel rich zones within the cylinder eliminates soot formation (1-pull Bosch smoke numbers of 0, 5-pull = 0). HCCI has been shown to reduce particulates by 27 percent. The limits of HCCI start of combustion timing are defined by knock BTDC and misfire ATDC.

Stable and repeatable HCCI combustion has been demonstrated over a wide range of air-fuel ratios (A/F), compression ratios (CR), EGR rates, and for two primary fuels. A/F ratios of 14 to 80 are possible. CR's of 8 to 13 have been demonstrated. EGR rates from 0 percent to 50 percent have been operated successfully. Stable combustion for diesel fuel as well as a blended fuel (19 percent hexadecane, 81 percent heptane) is possible.

What makes HCCI so successful is that the diesel fuel is fumigated into the intake air. The air charge, fuel and EGR is a homogeneous mixture when it enters the combustion chamber. There are no rich zones which are sites of soot production. The combustion also does not occur in a flame front as in conventional

DI and IDI engines. Combustion in a HCCI engine occurs uniformly initiated from many sites. This technology is the ultimate in fuel-air mixing since it is performed outside the cylinder.

HCCI is predicted to have higher specific fuel consumption than current technology DI engines. The reasons for this are as follows: (a) HCCI inlet air temperature is high, ~150 °C, which lessens volumetric efficiency; (b) HCCI utilizes large quantities of EGR and efficiency suffers due to "pumping" the inert gases; and (c) the HCCI engine operates at lower compression ratios than current DI engines.

This is currently not a production ready technology. The operating ranges of the HCCI engine must be defined and possibly expanded. In addition, a complex control system is required to control intake charge temperature and EGR rates. The current research in HCCI at SwRI is performed on a single-cylinder engine. Plans have been made to expand this work to a multi-cylinder engine platform. Further development is necessary to make this technology attractive.

## **5.0 OXYGEN ENRICHMENT**

Oxygen enrichment has generally be thought of as oxygenated fuels. With regards to better air utilization, oxygen enrichment is a method to increase the oxygen content in the intake air. DuPont Automotive's Compact Membrane Systems™ (CMS) group has developed a membrane that modifies air from 21 percent oxygen (by volume) to as high as 30 percent oxygen-enriched air (OEA).

Testing at Argonne National Labs has shown that OEA can provide an increase in engine power (range 40 to 70 percent), and improved fuel efficiency or a reduction in particulate (on the order of 75 percent). Prototypes have been fabricated which produce 1800 cubic feet (50,000 L) per hour at 25 percent OEA while consuming only 0.07 cubic feet (2.0 L) of space. CMS/DuPont are developing modules that produce 5,000-10,000 cubic feet (140,000-280,000 L) per hour.

Utilizing 25 percent OEA (volume basis) in an engine can potentially reduce the required mass flow of air by up to 15 percent. Using the size/volume information stated above and the peak air consumption for the dAIPS-type engine (14,900 lb/hr), the required membrane volume would be 6 cubic feet.

This is a technology that can increase air utilization by increasing the oxygen content in the air charge by removing nitrogen. CMS/DuPont are currently conducting demonstration tests and are evaluating various applications. The downside is that a large membrane, or multiple membranes, may be required for the use on a combat vehicle. Another potential limitation is the pressure drop across the unit. A trade-off between membrane size and engine power increases should be performed.



## **6.0 CONCLUSIONS/RECOMMENDATIONS**

The following is a summary of the possible fuel injection and combustion strategies to achieve higher diesel engine power density via improved air utilization.

### **6.1 Near-Term Technologies**

The following technology should be addressed for near-term solutions to better air utilization in diesel engines.

#### **6.1.1 Injection Equipment**

Utilize high pressure injection equipment that has flexible rate shaping. The most commercially viable systems are the High Pressure Common Rail (HPCR) and the Hydraulically actuated Electronically controlled Unit Injector (HEUI). Ideally, fuel injection systems that can initiate and control split injections (as many as three per cycle) are needed. Initial development should begin with pilot and main injections and then proceed with multiple injections. For this system, the smallest injector holes should be used. However, it should be noted that the number of holes should not be too numerous that the fuel jets overlap.

#### **6.1.2 Combustion Bowl**

The appropriate combustion chamber is the quiescent chamber to match the high injection pressures with a shallow combustion bowl. It is necessary to move the top piston ring as close as possible to the top of the piston crown to lessen the crevice volume, reduce the piston-to-head clearance, utilize flush mounted

valves, and eliminate valve pockets if possible. All of these items will contribute to increasing the air utilization.

#### **6.1.3 Increased Turbocharger Boost**

Increase air density by increasing the turbocharger boost directly decreases engine size by allowing smaller cylinders while producing the same power. Methods of controlling peak cylinder pressures must be employed. Ideally, increased cylinder pressure design limits are encouraged.

#### **6.1.4 Oxygen Enrichment**

DuPont Automotive has developed a membrane that increases oxygen content in the air (volume percent). A trade-off between space consumed and the pressure drop of the Compact Membrane System™ versus the power increase or engine reduction should be conducted.

### **6.2 Long-Term Technologies**

The most promising long-term technology is the Homogeneous Charge Compression Ignition (HCCI) combustion process. Fumigating diesel fuel in the intake with the proper ratio of EGR allows for true stoichiometric diesel combustion. Further refinement in control is necessary for this to be a viable solution. Other technologies such as multiple injectors or DI+IDI combustion chambers may be undesirable due to the extra hardware and control complexities.

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